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NOBLE GAS STUDY OF YAMATO-82192 LUNAR METEORITE

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Abstract: Concentrations and isotopic ratios of noble gases in matrix and glassy clast of the lunar meteorite Yamato-82192 are reported. Trapped gases are greatly depleted compared with other lunar meteorites (Yamato-791197 and Allan Hills A81005). However, the meteorite retains radiogenic ^{40}Ar quantitatively. The K-Ar age is 3.9±0.5 Ga, in good agreement with the ^{39}Ar-^{40}Ar age of Y-791197 and lunar highland rocks.

From the three-isotope plot of Ne and the abundance pattern of the trapped gas, the trapped gas is of solar-type. The cosmogenic ^{22}Ne/^{21}Ne and ^{131}Xe/^{126}Xe ratios suggest low shielding. A model to explain the noble gas data is that the meteorite is composed of a mixture of regoliths from different shielding depths. The regolith mixture was compacted to breccia by a meteorite impact and resided at the low shielding depth of less than 40 g/cm^2 for 20 to 40 m.y. The present specimen was produced from the interior of this regolith breccia by another meteorite impact and was thrown out to space. After the flight in space probably for less than 2 m.y., it fell in Antarctica.

1. Introduction

In the Antarctic meteorite collections, four lunar meteorites have been identified (Mason, 1982; Yanai and Kojima, 1984a; Yanai and Kojima, 1985; Yanai *et al.*, 1986). Yamato-82192 (hereafter Y-82192) is one of them. It has been classified as anorthositic breccia (Yanai and Kojima, 1984b). The lunar meteorites are important because they give information about new sites which have never been sampled by the Apollo and Luna missions.

Results of noble gas studies have been reported for Allan Hills A81005 (hereafter ALHA81005; Bogard and Johnson, 1983; Eugster *et al.*, 1986) and Y-791197 (Takaoka, 1986). Both ALHA81005 and Y-791197 contain great amounts of solar-type, trapped gases and excess ^{40}Ar. Their elemental abundances of the trapped gases are essentially identical with those of the lunar highland regolith. The ^{39}Ar-^{40}Ar age of Y-791197 has been determined to be 4065±93 Ma (Kaneoka and Takaoka, 1986), in good agreement with the age of lunar highland rocks. Very long cosmic-ray irradiation ages have been reported for Y-791197 and ALHA81005, suggesting that both stones resided at a shallow shielding depth on the moon for a long time. Results on radionuclides (Nishiizumi *et al.*, 1986), nuclear particle tracks (Crozaz, 1985) and thermoluminescence (Sutton, 1985) suggest a short transfer time of the meteorite from the moon to the earth.

These results give clear evidence for the lunar origin of these two meteorites. However, it is not apparent whether both meteorites originated by the same event or a different event on the moon. Further studies on these and other lunar meteorites are needed to solve the open question of their origin.

2. Sample and Experimental Procedure

Samples used in this work are Y-82192,63C (hereafter 63C) and Y-82192,64A (hereafter 64A). Sample 63C was chipped from a glassy clast which resulted from impact shock (YANAI, private communication). We have analyzed two samples (3.66 and 26.43 mg) from this clast. Another sample 64A is plagioclase-rich matrix. For matrix 64A, we have analyzed one sample (29.62 mg). The samples were wrapped in Al-foil (10 micron thick) and mounted in side arms of a sample holder which is made of glass. They were heated at about 150°C for 15 h to degas adsorbed atmospheric gases.

When sample 63C's were heated in the side arm, we found a pale bluish deposit on the inner surface of the side arm in which the sample 63C of 3.66 mg was mounted, but no deposit for the other samples. The appearance is similar to that of deposits observed for Quaternary volcanic rocks. Unfortunately we have not analyzed its chemical composition. It is suggested that the 3.66 mg sample contained a volatile-rich phase which is deposited on the low temperature part of the side arm. Such deposit was not observed for any other meteorite samples ever analyzed.

Noble gases were analyzed by conventional techniques of mass spectrometry which have been given elsewhere (TAKAOKA, 1976; TAKAOKA and NAGAO, 1978).

3. Results and Discussion

Results of noble gas analyses are summarized in Table 1. A result for Y-791197 is also given for comparison. Errors cited are statistical ones (one sigma). Uncertainties for noble gas concentrations are about 10%. For the decomposition of the gas mixture into trapped, radiogenic and spallogenic components, the following data are assumed: $({}^3\text{He}/{}^4\text{He})_{\text{sp}}=0.2$, $({}^3\text{He}/{}^4\text{He})_{\text{t}}=3.80\times10^{-4}$, $({}^{21}\text{Ne}/{}^{22}\text{Ne})_{\text{sp}}=0.80$, $({}^{20}\text{Ne}/{}^{21}\text{Ne}/{}^{22}\text{Ne})_{\text{t}}=12.5/0.0317/1$, $({}^{38}\text{Ar}/{}^{36}\text{Ar})_{\text{sp}}=1.55$, $({}^{38}\text{Ar}/{}^{36}\text{Ar})_{\text{t}}=0.189$, $({}^{40}\text{Ar}/{}^{36}\text{Ar})_{\text{sp}}=0$; for solar Kr and Xe, isotopic ratios for surface-correlated Kr (BEOC-12) given by EBERHARDT *et al.* (1972) and surface-correlated Xe (SUCOR-Xe) given by PODOSEK *et al.* (1971) are used, respectively. Yamato-82192 is quite different in the elemental abundances of trapped gases from those for the other lunar meteorites, as shown in Fig. 1. The abundances are lower by factors of more than 2200 for ^{4}He, 1300 for ^{20}Ne, 1600 for ^{36}Ar, 460 for ^{84}Kr and 340 for ^{132}Xe relative to those in the Y-791197 lunar meteorite. The trend of low noble gas abundances has been reported for another sample of this meteorite (WEBER *et al.*, 1986).

Trapped He is negligibly small in one sample (3.66 mg) of clast 63C and matrix 64A for which the He isotopic ratio is similar to that found in meteorites dominant in the spallogenic component. ^{3}He is mostly spallogenic. ^{4}He in 64A is a mixture of the spallogenic and minor radiogenic components, while 63C may retain a remnant

Table 1. Concentrations and isotopic ratios of noble gases in lunar meteorite Y-82192. Concentrations are given by cc/g.

Isotope	Y-82192,63C[a]	Y-82192,64A	Y-791197[b]
^{4}He ($\times 10^{-8}$)	99.1[c]; 204[d]	33.3	4.46×10^{5}
^{3}He/^{4}He	0.166±0.006[c] 0.0813±0.0016[d]	0.170±0.005	4.49×10^{-4}
^{22}Ne ($\times 10^{-8}$)	9.06	2.96	7550
^{20}Ne/^{22}Ne	7.97±0.07	2.13±0.04	12.30
^{21}Ne/^{22}Ne	0.319±0.004	0.708±0.012	0.0403
^{36}Ar ($\times 10^{-8}$)	22.7	7.18	3.39×10^{4}
^{38}Ar/^{36}Ar	0.274±0.002	0.422±0.041	0.189
^{40}Ar/^{36}Ar	52.8±0.4	79.8±1.5	2.536
^{86}Kr ($\times 10^{-10}$)	1.1	(1.6)[e]	521
^{78}Kr/^{86}Kr	0.0269±0.0012	—	0.0221
^{80}Kr/^{86}Kr	0.155±0.004	—	0.1361
^{82}Kr/^{86}Kr	0.694±0.020	—	0.6640
^{83}Kr/^{86}Kr	0.704±0.017	—	0.6678
^{84}Kr/^{86}Kr	3.327±0.090	—	3.266
^{136}Xe ($\times 10^{-10}$)	0.24	(0.38)[f]	74.0
^{124}Xe/^{136}Xe	0.0432±0.0070	—	0.0180
^{126}Xe/^{136}Xe	0.0528±0.0100	—	0.0183
^{128}Xe/^{136}Xe	0.319±0.021	—	0.284
^{129}Xe/^{136}Xe	3.00±0.15	—	3.407
^{130}Xe/^{136}Xe	0.521±0.045	—	0.554
^{131}Xe/^{136}Xe	2.45±0.16	—	2.728
^{132}Xe/^{136}Xe	2.96±0.12	—	3.311
^{134}Xe/^{136}Xe	1.151±0.067	—	1.232

(a) Weighted mean by sample weight, (b) Takaoka (1986), (c) 3.66 mg sample of 63C, (d) 26.43 mg sample of 63C, (e) ^{84}Kr, (f) ^{132}Xe.

of trapped He because the isotopic ratio of He for the 26.43 mg sample of 63C is low compared with that for the other samples.

Ne is a mixture of the trapped and spallogenic components. Trapped Ne is more dominant in 63C than in 64A. Figure 2 shows a three-isotope plot of Ne. Both 63C and 64A fall on a line connecting solar Ne (Ne-B) and spallogenic Ne, indicating that the trapped gas is of solar-type. The ^{22}Ne/^{21}Ne ratio for the spallogenic Ne is estimated to be 1.273 from the correlation line crossing with $(^{20}\mathrm{Ne}/^{22}\mathrm{Ne})_{\mathrm{sp}}=0.8$. This large ^{22}Ne/^{21}Ne ratio can be attributed mainly to a low Mg/Si ratio in the lunar meteorite. The ratio corrected for the Mg/Si ratio, target chemistry (Cressy and Bogard, 1976) is 1.165, suggesting low shielding.

Both ^{36}Ar and ^{38}Ar are mixtures of the trapped and spallogenic components, whereas ^{40}Ar is a mixture of the radiogenic and trapped ones. However, trapped ^{40}Ar is negligibly small because the ^{40}Ar/^{36}Ar ratio is high compared with that of Y-791197. Sample 63C contains 3.6 times more trapped ^{36}Ar than sample 64A. The ratio of trapped ^{20}Ne to ^{36}Ar is 3.3 for 63C, while it is 0.75 for 64A. This ratio for 63C is intermediate between the ratio (3.7–8.3) for mare soils and the ratio (2.1–2.9) for Apollo 16 highland soils (Kirsten *et al.*, 1973). Y-82192 is different in this respect from Y-791197 for which the ratio falls in the range for the Apollo 16 highland soils,

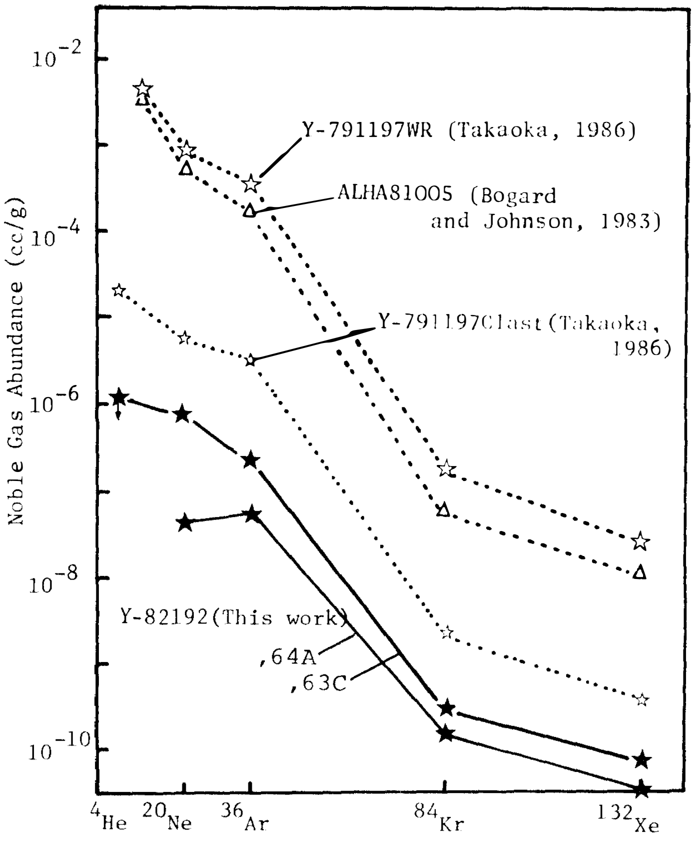

Fig. 1. Trapped noble gas abundance for lunar meteorite Yamato-82192.

and rather similar to ALHA81005. An average concentration of ^{40}Ar is 8.9×10^{-6} cc/g. With assumptions that the ^{40}Ar is all radiogenic and that the K content is 170 ppm (BISCHOFF *al.*, *et* 1986; FUKUOKA *et al.*, 1986; WARREN and KALLEMEYN, 1986), the K-Ar age is estimated to be 3.9 ± 0.5 Ga. This is in good agreement with the ^{39}Ar-^{40}Ar age for Y-791197 given by KANEOKA and TAKAOKA (1986).

As shown in Table 2, comparison of the trapped and spallogenic gases between 63C and 64A indicates that 63C is enriched progressively in lighter isotopes of both gases relative to 64A. One of reasons for such trend is a partial gas loss from 64A accompanied by the elemental fractionation. Apparently 63C contains an appreciable amount of trapped gas, and the three-isotope plot of Ne indicates that the trapped Ne in both samples is of solar-type (Fig. 2). These facts and the low $(^{20}\mathrm{Ne}/^{36}\mathrm{Ar})_t$ ratio for 64A suggest that 64A lost a large part of the light trapped gas. In addition, sample 64A is greatly depleted in spallogenic ^{3}He, while spallogenic ^{21}Ne and ^{38}Ar are not largely different between the two samples. The $(^{3}\mathrm{He}/^{21}\mathrm{Ne})_{sp}$ ratio for 63C is not far from the value inferred from the $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{sp}$ ratio and the correlation between $(^{3}\mathrm{He}/^{21}\mathrm{Ne})_{sp}$ and $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_{sp}$ (*e.g.* NISHIIZUMI *et al.*, 1980), while the ratio for 64A is significantly low. This also suggests the partial loss of spallogenic gases.

On the moon, ^{131}Xe is produced by resonance capture of epithermal neutrons by ^{130}Ba (EBERHARDT *et al.*, 1972) as well as the spallation reaction of galactic and solar cosmic-rays. Xe in 63C (26.43 mg) shows definite excesses in ^{124}Xe, ^{126}Xe and ^{128}Xe relative to solar Xe. However, correction for the trapped Xe of solar composition

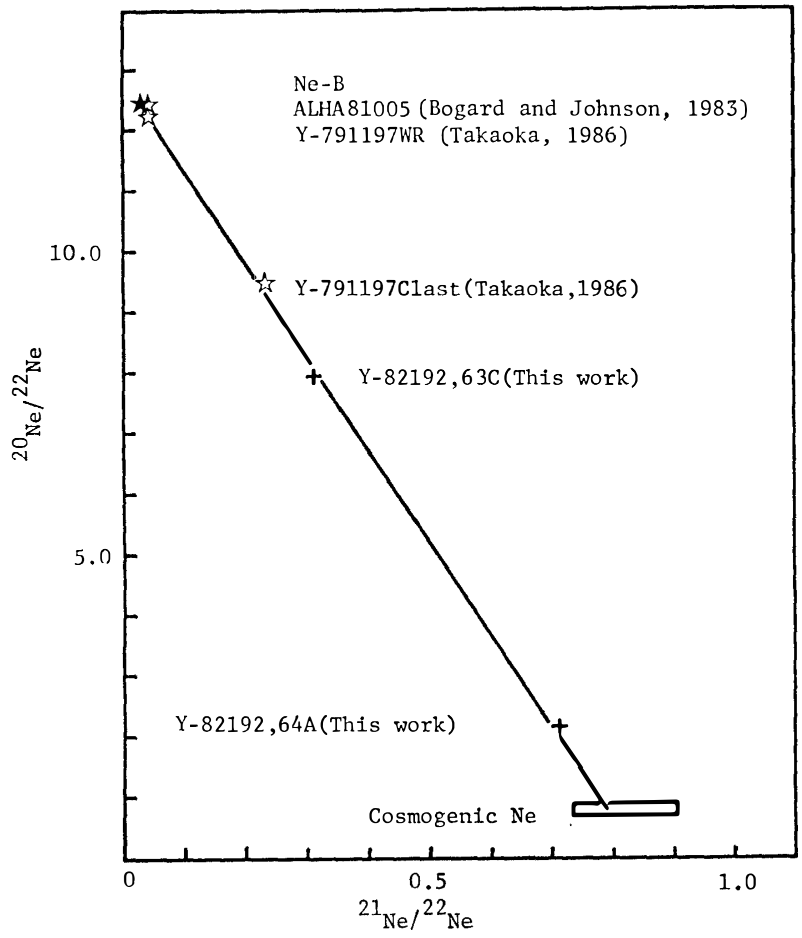

Fig. 2. Three-isotope plot of Ne for lunar meteorite Yamato-82192.

Table 2. Trapped and spallogenic components of noble gases in Y-82192.

Isotope	63C	64A	63C/64A
$(^{4}He)_t$ $(10^{-8}$ cc/g)	<105	≈0	—
$(^{20}Ne)_t$ $(10^{-8}$ cc/g)	71	4.4	16
$(^{36}Ar)_t$ $(10^{-8}$ cc/g)	21	6.0	3.6
$(^{84}Kr)_t$ $(10^{-10}$ cc/g)	3.7	(1.6)[a]	2.3
$(^{132}Xe)_t$ $(10^{-10}$ cc/g)	0.71	(0.38)[a]	1.9
$(^{20}Ne/^{36}Ar)_t$	3.3	0.75	4.4
$(^{3}He)_{sp}$ $(10^{-8}$ cc/g)	16.6	5.66	2.93
$(^{21}Ne)_{sp}$ $(10^{-8}$ cc/g)	2.71	2.09	1.30
$(^{38}Ar)_{sp}$ $(10^{-8}$ cc/g)	2.20	1.91	1.15
$(^{83}Kr)_{sp}$ $(10^{-12}$ cc/g)	4.4	—	—
$(^{126}Xe)_{sp}$ $(10^{-12}$ cc/g)	0.97	—	—
$(^{3}He/^{21}Ne)_{sp}$	6.13	2.72	2.25
$(^{21}Ne/^{38}Ar)_{sp}$	1.23	1.09	1.13

(a) From $(^{83}Kr)_{sp}$ and $(^{126}Xe)_{sp}$ for 63C, spallogenic components were assumed to be negligible.

gives negative values to the heavier isotopes. Correction for the trapped Xe of atmospheric composition gives the cosmogenic ($^{131}Xe/^{126}Xe$)=2.0±2.8. The low $^{131}Xe/^{126}Xe$ ratio indicates a shielding depth less than 40 g/cm^2 (HOHENBERG *et al.*, 1978).

As discussed earlier, the meteorite contains the trapped gas, but with great depletion compared with the other lunar meteorites. From the abundance pattern of trapped gas in 63C and the three-isotope plot of Ne, the trapped gas is of solar-type. A low shielding condition is inferred from ($^{22}Ne/^{21}Ne$)$_{sp}$ and $^{131}Xe/^{126}Xe$ for cosmic-ray produced Xe. The partial gas loss was suggested by comparison of the trapped and spallogenic gases between 63C and 64A. However, it is impossible to attribute the depletion of the trapped gas only to the gas loss because radiogenic ^{40}Ar is retained quantitatively. These mean that the history of Y-82192 is not simple.

A model to explain the noble gas data is that the meteorite is composed of a mixture between regolith containing practically no trapped gas (heavy shielding) and regolith which received the solar wind implantation at a low shielding depth, *e.g.* less than 40 g/cm^2. The fraction of the regolith of low shielding is very low from comparison of the trapped gases between 63C and Y-791197. A meteorite impact probably occurred 20 to 40 m.y. ago and gardened the lunar highland crust to mix the regoliths from different shielding depths. The regolith mixture was compacted to breccia by this impact. The regolith breccia resided at the low shielding depth and received a dose of galactic cosmic-rays. From the low abundance of trapped gas and the low shielding depth, it is inferred that the Y-82192 meteorite is a specimen from the interior of this regolith breccia.

Table 3 shows apparent ages of cosmic-ray exposure calculated with production rates for 2π geometry (HOHENBERG *et al.*, 1978; REGNIER *et al.*, 1979) and 4π geometry (CRESSY and BOGARD, 1976). In calculation of the cosmic-ray ages, we postulate a chemical composition given in Table 4. For the production rate of ^3He by the 2π irradiation, we use the halved rate given by CRESSY and BOGARD. The numbers

Table 3. Apparent cosmic-ray irradiation ages (m.y.) for Y-82192.

Sample	T_3	T_{21}	T_{38}	T_{83}	T_{126}
**2-π geometry (10 g/cm^2)^{a,b}					
63C	(13)^d	26	22	14	44
64A	(4.3)^d	20	19	—	—
**4-π geometry^c					
63C	6.3	9.7	9.9	(7)^d	(22)^d
64A	2.2	7.5	8.6	—	—

(a) HOHENBERG *et al.* (1978), (b) REGNIER *et al.* (1979), (c) CRESSY and BOGARD (1976), (d) Ages in parentheses were calculated by halving or doubling production rates estimated for another geometry.

Table 4. Chemical composition postulated for calculation of production rates of spallogenic gases. It is a mean of BISCHOFF et al. (1986), FUKUOKA et al. (1986) and WARREN and KALLEMEYN (1986).

Na	Mg	Al	Si	K	Ca	Ti	Fe	Rb	Sr	Zr	Ba	La
			(wt%)							(ppm)		
0.32	3.16	13.3	22.9	0.017	10.5	0.16	4.02	<3	165	24	24	1.33

Zr/Y=4 was assumed.

employed are 1.31 and 2.62×10^{-8} cc/g/m.y. for 2π and 4π irradiations, respectively. As summarized in Table 3, we find the best concordancy between ^{21}Ne and ^{38}Ar ages at a shielding depth of 10 g/cm^2 for the 2π geometry. The ^{21}Ne ages are larger by 20 and 6% than the ^{38}Ar ages for 63C and 64A, respectively. The ^{126}Xe age is longer by a factor of 2 than the ^{21}Ne and ^{38}Ar ages, whereas the ^{83}Kr age is a half of the ^{21}Ne age. This may be due to the inadequate chemical composition employed for calculation of the production rates and to the partial loss of spallogenic gas.

With the production rates for 4π geometry, the ^{21}Ne and ^{38}Ar ages are concordant especially for sample 63C, whereas both ages for 64A are not largely different from those for 63C. However, it should be mentioned that NISHIIZUMI *et al.* (1980) have reported the production rates of ^{21}Ne for chondrites which are about 50% lower than those given by CRESSY and BOGARD. Unfortunately NISHIIZUMI *et al.* have not given the production rates for achondrites. However, if this difference in the production rate is not different significantly between chondrites and achondrites, then the age might be about 50% longer than that calculated by CRESSSY and BOGARD (1976).

The ^{3}He ages are discordant not only with the ^{21}Ne and ^{38}Ar age, but also between 63C and 64A. An approximately equal concentration of spallogenic ^{38}Ar in 63C and 64A suggests that both samples experienced the same dose of cosmic-ray irradiation on the moon and in space. Therefore, the discordant ^{3}He age is attributed mainly to the loss of spallogenic ^{3}He, probably by the shock of a meteorite impact which ejected the present specimen to space. With an assumption that the retention of spallogenic gas produced in space was complete, we could adopt the ^{3}He age for 64A as an upper limit of a transit time from the moon to the earth.

4. Summary

We can infer a history of the Y-82192 lunar meteorite as follows: Material compacted to the Y-82192 is a mixture between regolith of heavy shielding and a minor fraction of regolith of low shielding. A meteorite impact which occurred 20 to 40 m.y. ago gardened the lunar highland crust to mix the regoliths from different shielding depths and to compact them to a regolith breccia. The breccia resided at the low shielding depth, *e.g.* less than 40 g/cm^2, and received a dose of galactic cosmic-rays. The interior of the breccia was shielded from the solar-wind implantation. By another meteorite impact which occurred less than 2 m.y. ago, several fragments were ejected to space. The Y-82192 meteorite is one of them and a specimen from the interior of this regolith breccia.

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